THE ION BEAM SHEPHERD: A NEW CONCEPT FOR ASTEROID DEFLECTION

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ABSTRACT

A novel slow push asteroid deflection strategy has been recently proposed [1] in which an Earth threatening asteroid can be deflected by exploiting the momentum transmitted by a collimated beam of quasi-neutral plasma impinging against the asteroid surface. The beam can be generated with state-of-the art ion engines from a hovering spacecraft with no need for physical attachment nor gravitational interaction with the celestial body. The spacecraft, placed at a distance of a few asteroid diameters would need an ion thruster pointed at the asteroid surface as well as a second propulsion system to compensate for the ion engine reaction and keep the distance between the asteroid and the shepherd satellite constant throughout the deflection phase. The key aspects of the concept are discussed.

INTRODUCTION

The deflection of an asteroid from its collision course with our planet is, in principle, technically feasible and can be carried out in different ways. The basic idea is to transmit an impulsive or continuous force to the asteroid whose effects is to eventually produce a large enough shift on the asteroid intersection point on the Earth b-plane in such a way that the impact with our planet can be ruled out with a high enough degree of confidence.

Such force can be transmitted in an impulsive manner by use of a stand-off nuclear explosion or simply by having a spacecraft impacting against it at high relative velocity. The latter method, often referred to as kinetic impactor (KI) is one of the preferred asteroid deflection methods, mostly due to the fact that the technique has been successfully demonstrated by the NASA Deep Impact mission in 2005. In that mission, a 370-kg impactor collided at 10.3 km/s relative velocity with the nucleus of the P/Tempel 1 comet. Nevertheless, impacting at a similar speed against a typical 150 m diameter asteroid, roughly 40 times smaller than the above comet, would require advances in the field of guidance and navigation not to be underestimated.

A radically different strategy consists of building up the required deflection with a long-duration slow push transmitted to the asteroid by a rendezvous spacecraft. The key advantage of this solution is that, unlike the impact methods, the deflection can be carried out in a precise manner, which is important when one has to avoid secondary impacts as a result of the asteroid passing through resonance keyholes in the b-plane. In addition, slow-push methods do not bear the risk of fracturing the target asteroid, which may be fragile especially when in a fast rotational state.

Among the "slow-push" methods the gravity tractor (GT) concept, proposed by Lu and Love in 2005 [2], is regarded as one of the most promising. When using a GT the deflection can be achieved without physical contact between the spacecraft and the asteroid and can be predicted very accurately once the distance and the mass of the asteroid and the spacecraft are known, irrespectively of the asteroid surface and structural properties.

However, the gravity tractor concept suffers from at least two major drawbacks [1]. The first is the need for a massive spacecraft to physically produce the gravitational force required to slowly deflect the asteroid. The second is the difficulty of controlling the (unstable) proximity hovering position of the spacecraft for a large period of time avoiding undesired collisions.

The recently proposed ion beam shepherd concept (IBS) [1] promises to overcome these limitations by using the momentum of impinging propellant ions rather than gravity to achieve a contactless slow-push deflection, whose magnitude does not depend on the spacecraft and asteroid mass but rather on the characteristics of the power and propulsion system employed. Low-divergence ion thrusters tested in previous space missions can be used for this purpose without the need of substantial modifications, although an improvement in terms of specific impulse and beam divergence would increase the IBS capability.

The key aspects of the concept, which has been also proposed for active space debris removal [3], are summarized in this article.

CONCEPT DESCRIPTION

The IBS concept is schematized in Fig. 1. The shepherd spacecraft is located not too far from the asteroid, pointing one of its ion thrusters directly at the asteroid surface. The high-velocity ions of the quasi-neutral plasma emitted by the thruster reach the asteroid surface penetrating the asteroid material while losing their energy through ionizing collisions until they (suddenly) stop a few nanometers below the surface. If the beam fully intercepts the asteroid surface the latter will undergo a force roughly equal and opposite to the one experienced by the spacecraft. It will then be necessary to have a second ion thruster mounted on the spacecraft to cancel out the total force and keep constant the distance with respect to the asteroid. Note that the IBS gravitational pull on the asteroid, which would, in principle, reduce the transmitted momentum is typically negligible for reasonable hovering distances [1].

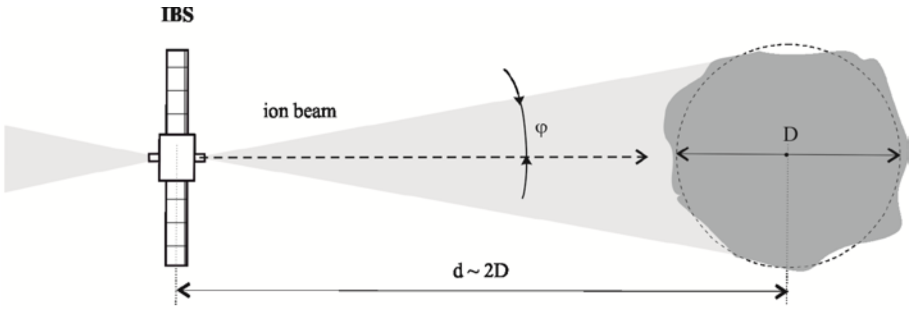

Fig. 1. Schematic of asteroid deflection with an ion beam shepherd

IBS MASS COST

When the deflection starts a few years before the impact event, as it is typically the case for slow-push methods, and no intermediate planetary flybys occur, the optimum push strategy consists of changing the asteroid semimajor axis in such a way that it will arrive at the predicted impact location with an accumulated time delay. This, in turn, produces a shift along the ζ axis of the b-plane which almost coincides with the total achieved deflection (the shift along the ξ axis, which corresponds to the minimum orbit intersection distance or MOID, is usually negligible). In order to produce the maximum variation of semimajor axis over a finite time interval the thrust direction has to be aligned with the primer vector of the Hamiltonian constructed around the final orbital energy to be maximized. For extremely small accelerations, as it is the case here, such vector is virtually coincident with the tangent to the orbit.

If for simplicity we assume the applied force F is constant and the primary and secondary propulsion systems are identical, the total mass m_{tot} needed for such a slow-push campaign of duration Δt can be divided into fuel, power plant and structure:

$$m_{tot} = 2\left[\frac{F\Delta t}{I_{sp}g} + \frac{\alpha F \cdot I_{sp}g}{2\eta}\right] + m_{str}$$

where I_{sp} is the (constant) thruster specific impulse, g is the see-level gravity, η the thruster efficiency, m_{str} the spacecraft structural mass (excluding the power plant) and α the inverse specific power, also considered constant.
Figure 2 plots the achievable deflection for an IBS system as a function of the desired push time and for two different values of the specific impulse.

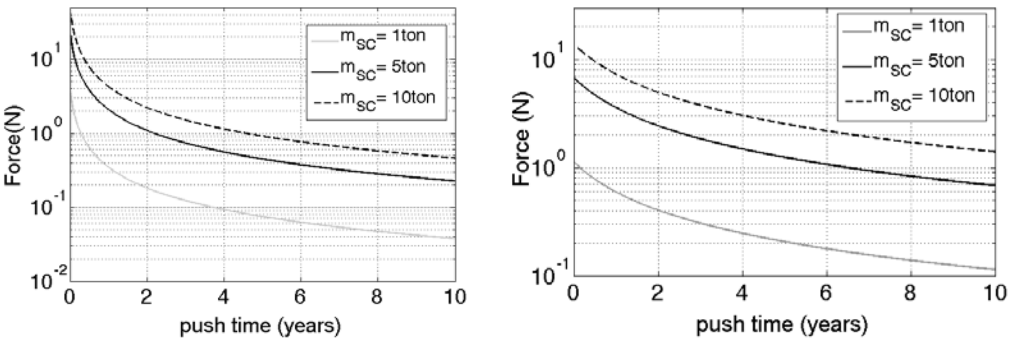

Fig. 2. Deflection force achievable as a function of the push time for different IBS masses and considering a specific impulse of 3000s (left) and 10000s (right). Thruster efficiency is set to 70%, inverse specific power to 5 kg/kW, and structural mass to 150 kg.

For a comparison, the mass m_{GT} of a gravity tractor providing a pull force F cannot be smaller than:

$$m_{GT} = \frac{F d_{hov}^2}{G m_{ast}} = \frac{3 F d_{hov}^2}{4 \pi G \rho_{ast} \left(D_{ast}/2 \right)^3}$$

where d_{hov} is the hovering distance measured from the asteroid center of mass, G is the gravitational constant, and m_{ast} , ρ_{ast} and D_{ast} are the asteroid mass, density and diameter, respectively. Assuming a typical hovering distance of 1.5 asteroid diameters we have:

$$m_{GT} = \frac{27 F}{8 \pi G \rho_{ast} D_{ast}}$$

which is plotted in Figure 3 showing that the mass cost to obtain moderately high deflection forces is considerable, especially for small asteroids.

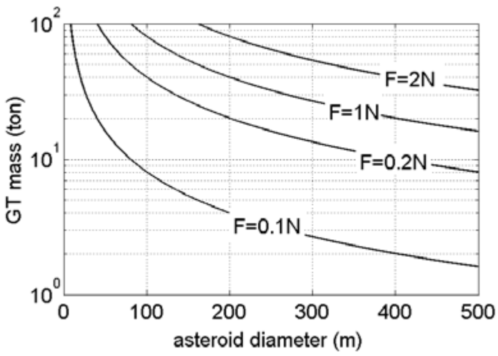

Fig. 3. Gravity tractor mass needed in order to produce a given deflection force F as a function of the asteroid diameter. Hovering distance is assumed equal to 1.5 asteroid diameters while asteroid density is set to 2.0 g/cm^3.

DEFLECTION PERFORMANCE

In order to assess the achievable deflection in a real mission scenario we have considered the asteroids 2007 VK_{184} and 2009 AG_5 , currently the only two NEOs having index 1 with respect to the Torino scale, and applied a continuous tangential thrust acceleration throughout a given time interval before the impact. The orbital elements of the two asteroids, of 130m and 140m diameter respectively, have been slightly modified in order to have an impact at the Earth centre at the time of the predicted closest approach. The analytical method of ref. [4] has been used to estimate the deflection, for which the effect of the Earth gravitational interaction is (conservatively) neglected for clarity.

Figure 4 plots the deflection achievable with a continuous tangential push of magnitude 1N applied to both asteroids continuously for 2 or 10 years and starting 10 years before the predicted impact.

The 2-years strategy appears very promising as it is enough to produce a deflection of 2 earth radii and can be carried out with a total spacecraft mass of about 5 tons with a 3000s specific impulse ion engine (Fig.2a), or with about 2.2 tons should a 10000s specific impulse ion engine become available in the near future (Fig.2b). Note that in order to achieve a 1N continuous thrust force a whopping 50-ton gravity tractor would be needed (Fig.3).

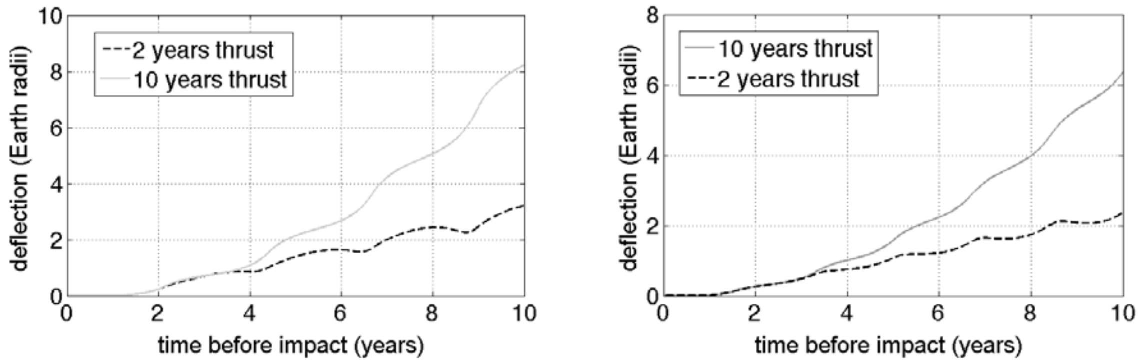

Fig. 4. b-plane deflection for constant tangential thrust acceleration (*F*=1 N) applied to the asteroid $2007VK_{184}$ (left) and $2009AG_5$ (right) with a 10-year warning time.

Table 1. Main characteristics of the two chosen asteroids

	2007 VK_{184}	**2009 AG_5**
mass (kg)	3.3×10^9	3.9×10^9
diameter (m)	130m	140m
semimajor axis (AU)	1.726	1.43
eccentricity	0.57	0.39
inclination (deg)	1.22	3.68

CONCLUSIONS

In this article we have introduced the main characteristics of the recently proposed ion beam shepherd concept (IBS), showing that the method can be effectively used to deflect a typical 140 m diameter asteroid with reasonable lead time (10 years from impact) and reasonable spacecraft mass (<5 tons). Technological advances in the area of ion propulsion, deployable solar arrays as well as guidance and navigation will be key in order to improve the performance and technological readiness of the concept.

ACKNOWLEDGEMENTS

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